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DISTRIBUTION PATTERNS OF GYPSUM AND KALISTRONTITE IN A DRY LAKE BASIN OF THE SOUTHWESTERN KALAHARI (OMONGWA PAN, NAMIBIA)

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ABSTRACT

The deposits of the Omongwa pan, southwestern Kalahari, Namibia, are partly gypsiferous and locally contain small amounts of kalistrontite. The distribution patterns of gypsum ($CaSO_4.2H_2O$) and kalistrontite ($K_2Sr(SO_4)_2$) are mainly determined by groundwater depth and by the lithological composition of the deposits. The latter determines the hydraulic conductivity for saturated and unsaturated flow and therefore controls the depth of the interval within the deposits where evaporation and mineral precipitation can take place. Other factors that affect the distribution of the evaporite minerals are the patterns of groundwater flow within the basin and the occurrence of a redistribution of salts during short flooding stages.

Gypsum occurs as crystals of four distinct morphological types, which each developed in different conditions: *prismatic crystals* formed both as subaqueous precipitates and as crystals that developed within the sediment matrix of a brine-saturated surface layer; sub/euhedral *tabular crystals* formed within brine-filled macropores; *hemi-bipyramidal crystals* formed in a nearly permanently brine-saturated part of a subsurface horizon (phreatic zone), as the product of recrystallization of an older gypsum occurrence; and *lenticular crystals* formed by intrasediment growth in the vadose zone. The development of these morphological types of gypsum crystals is marked by differences in the differential inhibition of growth of the various crystal forms. The further growth of lenticular crystals, which are most strongly affected by differential growth inhibition, is still characterized by a difference in degree of inhibition between the $\{\bar{1}11\}$ and $\{\bar{1}03\}$ forms, expressed as a change in orientation of the plane of flattening. Copyright © 1999 John Wiley & Sons, Ltd.

KEY WORDS: gypsum; kalistrontite; evaporite distribution patterns; gypsum crystal habit; Kalahari; Namibia

INTRODUCTION

An understanding of the mechanisms of water and solute movement in soils is commonly used to explain vertical variations in moisture content and total dissolved solids concentrations in soil profiles. The implications of these models for distribution patterns of evaporite minerals are, however, only rarely considered. In this study, the distribution of gypsum ($CaSO_4.2H_2O$) and kalistrontite ($K_2Sr(SO_4)_2$) in a dry lake basin is discussed mainly by referring to those models. In the second part of the text, the development of different types of gypsum occurrences, which are each characterized by a specific crystal habit, are related to various aspects of the movement of brines.

The studied basin is a pan of the southwestern Kalahari, in eastern central Namibia. These dry or ephemeral lake basins are common geomorphic features of the southern part of the Kalahari (Goudie and Thomas, 1985; Shaw, 1988; Verhagen, 1990; Marshall and Harmse, 1992; Goudie and Wells, 1995). Most of the studies of these basins have only dealt with the pans as landforms, without being concerned with the nature of their deposits.

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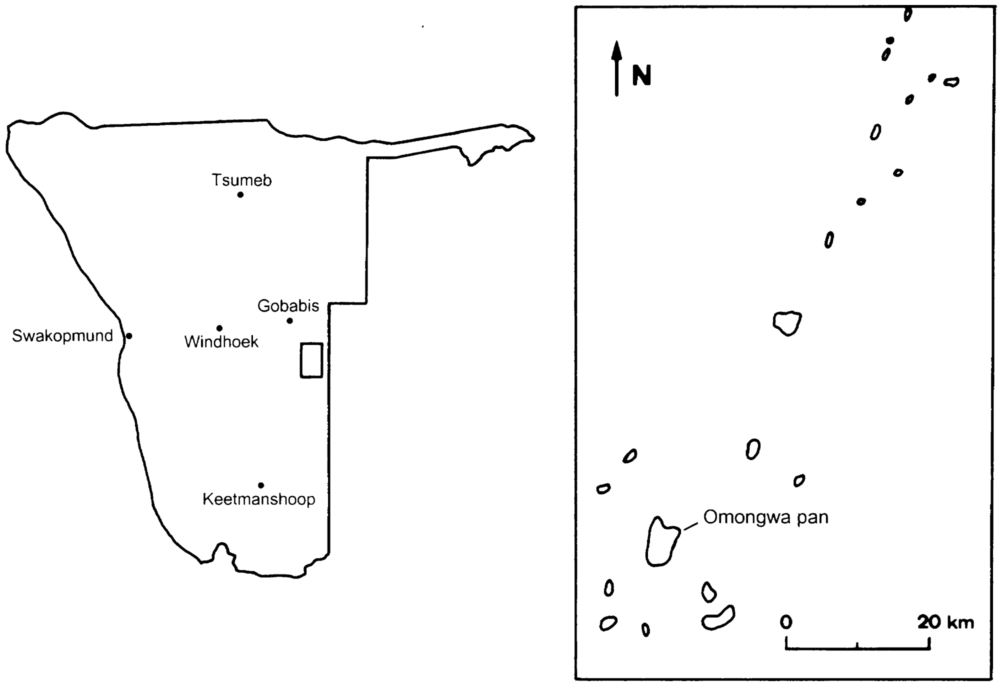

Figure 1. Location of the Omongwa pan in Namibia

MATERIAL AND METHODS

The site was visited both at the end of the rainy season (February 1991) and at the end of the dry season (November 1992). Most samples of the pan deposits were obtained from shallow profile pits (see Figure 2) whose base was mainly at a level within Unit III (see Figure 3), below the kalistrontite and main gypsum occurrences. Information about the older deposits was obtained mainly through augering. These older deposits were only studied to provide a context for the interpretation of the salt mineral occurrences in higher parts of the profiles and were sampled less extensively than the younger deposits.

Undisturbed samples were collected for the preparation of thin sections, of which 69 were used for this study. Bulk samples of the same intervals were used for routine textural and mineralogical analyses. Gypsum contents were determined by thermogravimetric analysis. Mineral identification is based on X-ray diffraction analyses and/or thin section observations, supplemented by energy dispersive X-ray analyses for some samples.

SETTING

General features

The Omongwa pan is located near Aminuis, 140 km SSE of Gobabis in eastern Namibia (Figure 1). It is one of a series of pans that appear to be aligned along a former branch of the Nossob River system, with a southward palaeodrainage direction (Kautz and Porada, 1976; Lancaster, 1986). In a wide area around the pan, the thickness of the Kalahari Group cover is less than 10 m and the pre-Kalahari substrate, which is locally exposed, consists of a dolerite sill (Geological Survey Namibia, 1979). Natural springs, representing groundwater discharge points, occur along the pan margin in the northern part of the basin, as well as at Rietquelle and near the Roman Catholic mission (Figure 2). A low earth dam has been constructed around the

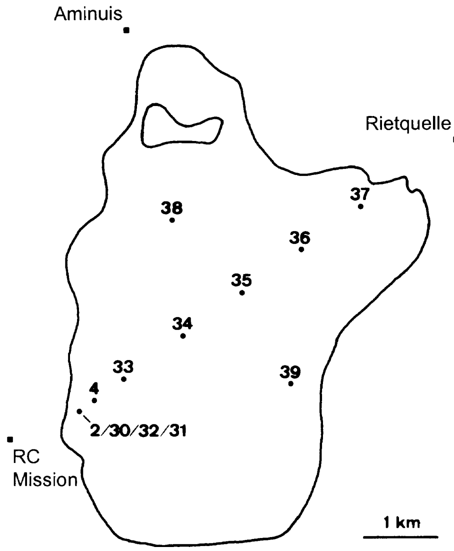

Figure 2. Location of the sampling sites mentioned in the text. Sites 2, 30, 32 and 31 are respectively located at 150, 200, 250 and 300 m from the southwestern end of the transect

spring at the latter of these sites, resulting in the development of a small freshwater pond. The surface of the Omongwa pan is dry during most of the year, except for periods of a few days following heavy rainfall. Average annual rainfall is about 250 mm at Aminuis, average annual evaporation from a Class A pan amounts to 3200 mm, and average summer and winter temperatures are 27°C and 12°C respectively (Von Jeney, 1982).

Pan deposits and subsurface occurrence of brines

The pan deposits consist of the same succession of four lithological units at most sampling sites (Table I; Figure 3). In the northeastern part of the basin, at site 37, only a thin layer of Unit IV deposits overlies a calcareous mudstone. At site 36, Unit IV covers a coarse-grained deposit that consists mainly of sand-sized detrital mineral grains and rounded calcareous sediment aggregates. Throughout the basin, Unit IV is characterized by the same type of horizonation (Table I; Figure 4). These patterns are related mainly to a higher organic matter content in the upper part of the profiles (IVa to IVc) and to a low free iron content in the basal part (IVe). The latter indicates the persistence of reducing conditions during prolonged periods when the deposits were water-saturated at those depths. Unit IV and the uppermost part of Unit III are crossed by vertical channels, whose number decreases with increasing depth below the IVc horizon. The infillings of these voids consist mainly of cylindrical excrements of soil organisms.

At the end of the rainy season, a brine-saturated interval occurred along the contact between Unit III and the dry deposits of Unit II at one site (site 2). At all other sites that were sampled during the same period, brine levels rose at a fast rate in the observation pits and stabilized at levels within Unit IV. Subsurface brines that were sampled during this period have a total dissolved solids concentration of about 260 g l^{-1} and are Na–K–Cl–SO_4 dominated.

At the end of the dry season, the occurrence of brine-saturated intervals was largely confined to Unit I. The lower part of the highly gypsiferous interval at the top of Unit II at site 34 represented the only higher occurrence. The deposits below this interval were characterized by a very low moisture content and a firm consistency. No brine-saturated intervals occurred at the same level at other sites. The equally highly gypsiferous interval along the top of Unit II at site 33 has a paler colour than the lower part of the same unit, indicating periodic or past hydromorphism.

These observations indicate that a perched water table fluctuates between the boundary between Units II and III and a level within Unit IV. The permeability of the highly calcareous, sepiolitic Unit III deposits is

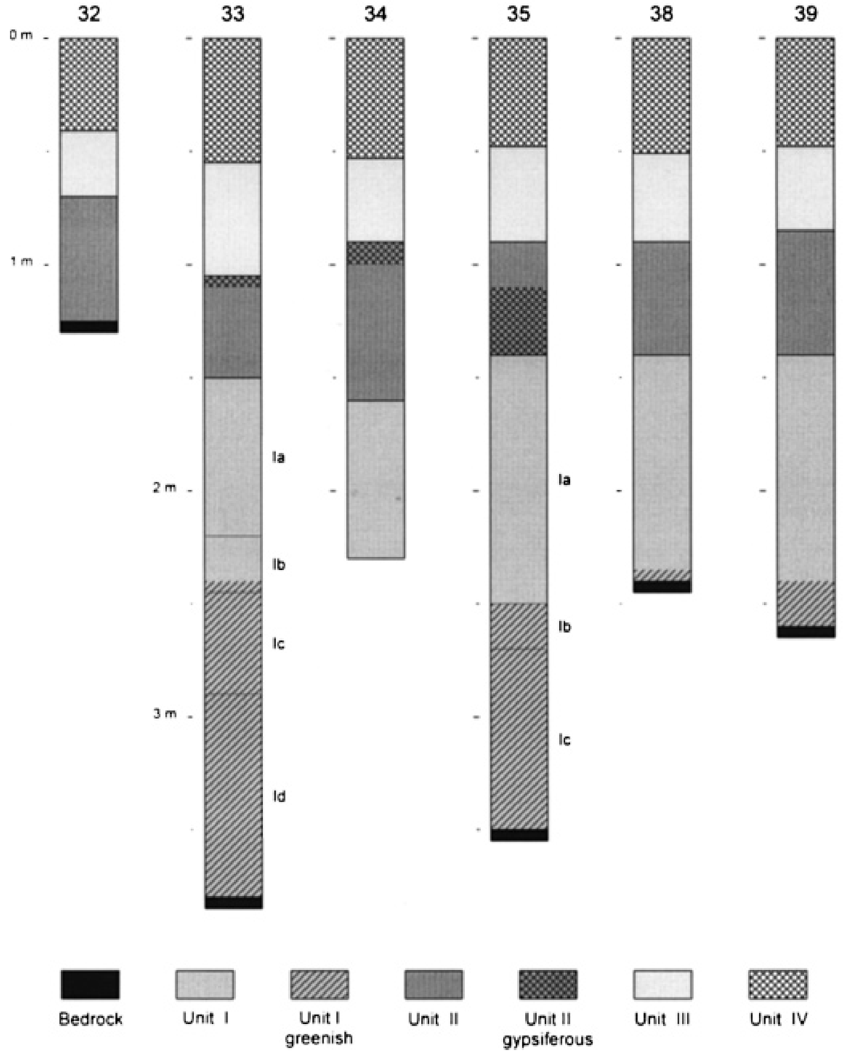

Figure 3. Simplified lithological logs of the deposits of the Omongwa pan for selected sampling sites. Only macroscopic gypsum occurrences are indicated for Unit II

clearly quite high, despite their fine grain size. The Unit II deposits, on the other hand, have a hydraulic conductivity that is sufficiently low to support a groundwater body, as a result of their heavier texture and despite a higher sand content. This conclusion is supported by the observation that the deposits of Unit IV, which are very similar to those of Unit II, seem to confine the brine within Unit III to some extent.

RESULTS AND DISCUSSION

Distribution patterns: gypsum

Gypsum occurs in all or some horizons of Unit IV throughout the basin, with variations within and between the profiles (Figure 5). In Unit III, gypsum occurs only along cracks, in parts that are adjacent to gypsiferous sections of the higher unit. The Unit II deposits are gypsiferous at at least three sites (33, 34 and 35), where gypsum occurs as large crystals (up to 4 cm) in intervals with a high gypsum content (44, 59 and 22 per cent,

Table I. General features of the pan deposits of the Omongwa basin

Unit	Horizon/ subunit	Colour	Sand* (%)	$CaCO_3$eq* (%)	Carbonate mineralogy †	Clay mineralogy ‡	Other features
IV	IVa	2·5Y 3/2	49·1	11·6	Ca	Sp, M, (Sm)	Mainly gypsiferous, in all horizons;
	IVb	2·5Y 3/2	26·6	15·2	Ca	Sp, M, (Sm)	high halite content in IVa (33·7%);
	IVc	2·5Y 3/2	33·2	11·8	Ca	Sp, M	kalistrontite along base of the unit;
	IVd	10YR 4/4	37·0	10·3	Ca	Sp, M	soft consistency of IVa and IVb,
	IVe	2·5Y 5/3	22·5	18·5	Ca	Sp, M	firm consistency of all other parts
III	-	5Y 6/2	3·6	57·0	Ca, Ar	*Sp*	Gypsum along cracks in upper part
II	-	5Y 5/3	41·7	14·5	Ca	Sp, M	Partly gypsiferous
I	Ia	2·5Y 5/2	4·3	59·1	Ca, Do	*Sp*, (M)	No gypsum, throughout the unit
	Ib	as Ia or Ic	21·9	25·3	Ca, Do	Sp, M	
	Ic	7·5GY 8/1	13·5	79·1	Do	M, Sp	
	Id	7·5GY 8/1	40·7	45·2	Do	*Sp*, (M)	

* Sand and $CaCO_3$eq %: average values, except for Unit I (values for site 33)
† Carbonate mineralogy: Ca, calcite; Ar, aragonite; Do, dolomite
‡ Clay mineralogy: Sp, sepiolite; *Sp*, sepiolite with low degree of structural order; M, muscovite; Sm, smectite.

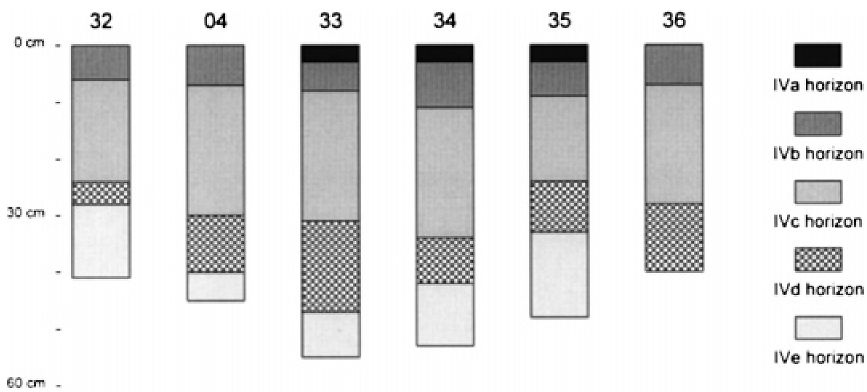

Figure 4. Succession of horizons within Unit IV, at some of the sampling sites that are located along the SW–NE transect through the pan basin

respectively). At site 33, the main part of this unit contains an equally high amount of gypsum (51 per cent), occurring as crystals with a much smaller size (75 μm to 2 mm). Because this gypsum occurrence was not recognized in the field, similar occurrences may have been overlooked at sites where the same interval has not been sampled.

Two other important aspects of the distribution patterns are the occurrence of non-lenticular gypsum crystals within voids (see Table II) and the presence of moulds of lenticular crystals in the lower part of Unit IV. The moulds are most abundant in the southwestern part of the basin, where they occur up to levels within the IVd horizon. At other sites, they occur only along the boundary between Units IV and III.

Interpretations of the distribution patterns of evaporites in soils must be based upon the principle that these minerals form only at levels where evaporation takes place. A prerequisite for the occurrence of evaporation is that transport of water takes place partly in the vapour phase. Its occurrence is therefore restricted to that part of the unsaturated zone that is between a level where the contribution of water transport in the vapour phase becomes significant and a level where transport in the liquid phase ceases (i.e. the evaporation front). The latter can be located at or below the surface. Evaporation occurs throughout an interval below the evaporation front, with a downward decreasing intensity. Because an enrichment in solutes takes places at points where soil water evaporates, the depth and other characteristics of this interval will partly determine

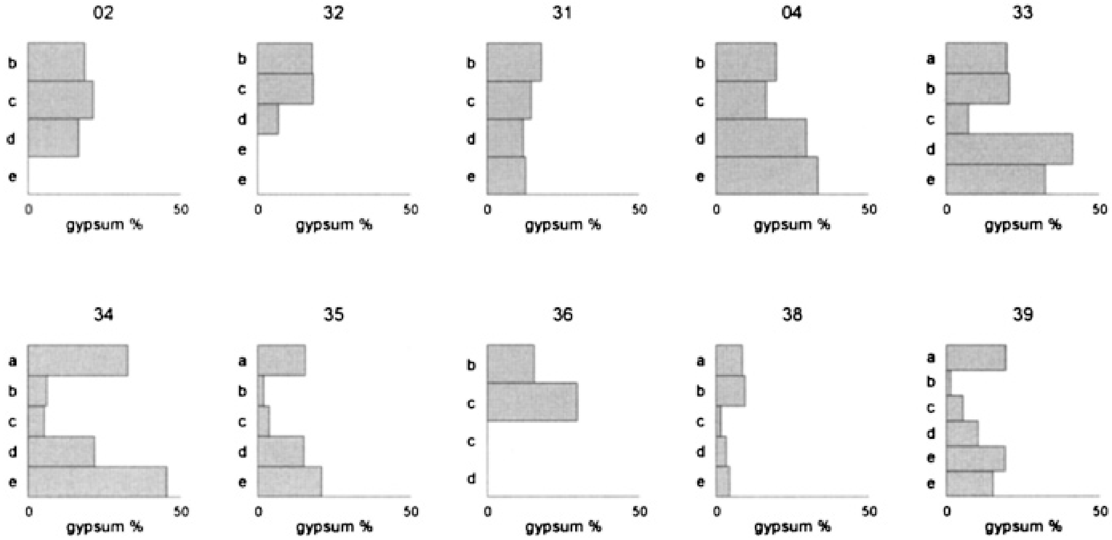

Figure 5. Vertical variations in gypsum content between successive horizons of Unit IV for selected profiles

the vertical distribution of evaporites that form as groundwater precipitates. Although salt minerals will form throughout a specific depth interval, saturation with respect to any mineral will in any case always first be reached at the evaporation front.

A first important aspect of the distribution of gypsum in the Omongwa basin is its absence within the matrix of the Unit III deposits. This absence is not conditioned by a low hydraulic conductivity of the Unit III sediments, in view of the previously reported observations regarding the presence of brine-saturated intervals. Instead, it must be concluded that no movement of water takes place in the vapour phase within the fine-grained, sepiolitic, highly calcareous deposits, which do have a high hydraulic conductivity for water transport in the liquid phase. Within Unit III, evaporation can take place only along cracks, which represent sites where gypsum commonly occurs in the profiles.

Vertical variations in gypsum content within Unit IV are determined by the position of the evaporation front during periods of gypsum saturation and by variations of the depth of that level with time. This depth is partly determined by the depth of the top of the saturated zone, which varies rather widely and is greater than the depth of the base of Unit IV during most of the year. The evaporation front is never located within Unit III, except where it penetrates this interval along cracks. When the groundwater level is below the boundary between Units III and IV, the evaporation front is located within Unit IV, at a depth that is determined by the thickness of the unsaturated zone within Unit III and by the water content of the Unit IV deposits.

The gypsum distribution patterns for Unit IV (Figure 5) show that, in most parts of the basin, the evaporation front was nearly always located below the soil surface when gypsum saturation was reached. The downward decrease in gypsum content that would be produced by mineral precipitation in a soil with an evaporation front at the surface occurs only in marginal parts of the basin, at site 31. Gypsum predictably also formed during periods with a greater depth of the evaporation front at this site, as shown by the limited steepness of the gradient and by its reversal in lower parts of the interval. The other profiles in this peripheral part of the basin (sites 2, 30 and 32), located at a shorter distance from the margin than site 31, may originally have been characterized by a similar downward decrease in gypsum content. These profiles have, however, been affected by a dissolution of gypsum in lower parts of the unit, as demonstrated by the presence of gypsum crystal moulds in the (partly) non-gypsiferous IVe and IVd horizons, which has altered these patterns at a later stage.

The prominent maximum in gypsum content in lower parts of the interval at sites in more central parts of the basin (sites 33, 34 and 35) shows that the average depth of the evaporation front was greater in this area.

This difference is related to a greater depth of the groundwater table, conditioned by variations in depth of the top of Unit II (see Figure 3), which is the confining layer in higher parts of the deposits. This lateral variation in groundwater depth is also expressed by the change in depth of the base of the IVd horizon (see Figure 4). The smaller range of the variations in gypsum content at site 4 in comparison with the less marginal sites is in agreement with the suggested dependence on groundwater depth, because the evaporation front will commonly be at a greater depth at this site. At sites 38 and 39, where the boundary between Units II and III occurs around the same depth as at sites 33 to 35, the gypsum distribution patterns are identical to those that developed at those other sites. The low gypsum content at site 38 records a low groundwater salinity in the northern part of the basin that appears to be determined by the patterns of groundwater flow within the palaeodrainage channel in which the pan is located.

The gypsum distribution patterns are not compatible with the high groundwater levels that were maintained during the long period of hydromorphism that affected the lower part of Unit IV, resulting in the development of the IVe horizon. This implies a lowering of the groundwater level and an increase in groundwater salinity with time. The later change in hydrological conditions that resulted in a dissolution of gypsum in lower parts of Unit IV in the southwestern part of the basin must involve a temporary or periodic increase in groundwater levels, leading to a permeation of those parts of the unit by undersaturated groundwater. However, the groundwater level cannot have been maintained at a shallow depth (such as the depth of the top of the interval with gypsum crystals moulds) for long periods of time, because the resulting increase in evaporation rates would ultimately lead to an increase in salinity. This change in groundwater level may have a local cause, such as the artificial ponding of the spring along the southwestern pan margin. The occurrence of long-term changes in average groundwater depth and in the amplitude of seasonal variations, as well as the possible occurrence of natural or human-induced changes in hydrological conditions, imply that gypsum distribution patterns that are observed today do not necessarily reflect the nature of present-day spatial and temporal variations in groundwater depth. In this way, the lower groundwater level at site 2 than at somewhat more basin-central sites at the end of the rainy season does not invalidate the proposed dependence of gypsum distribution patterns on groundwater depth.

At site 36, gypsum occurs only in the upper part of Unit IV. Groundwater levels are lower at this site than in other parts of the basin, as suggested by the absence of a IVe horizon. In addition, the lower part of Unit IV at this site cannot be affected by the strong gypsum enrichment that took place in profiles where the deposits of Unit III underlie this interval, because of the low hydraulic conductivity for unsaturated flow of the coarse-grained sediments below Unit IV in this part of the basin. All gypsum that occurs at this site can therefore only be derived from the surface. Because no source area for an aeolian supply exists, gypsum can only have been added to the surface by a redistribution within the basin. This involves the dissolution of gypsum that formed at or near the surface in marginal parts of the pan, where the groundwater table occurs at shallow depth, and their subsequent dispersal over the entire volume of the water body that occupies part of the basin after heavy rainfall. The surface level of this ephemeral water mass may be high enough to reach these marginal parts, but because water bodies of this type are readily displaced by wind (e.g. Torgersen, 1984) they can easily extend over parts of the pan floor that would not be covered in equilibrium conditions.

This redistribution is a long-term process involving the repeated dissolution and reprecipitation of salts. It accounts for the high gypsum and total soluble salt contents of the surface horizon in all parts of the basin where this enrichment cannot be due to a *per ascensum* mechanism of mineral precipitation, which includes the entire central part of the basin. The salts that are formed in this way are ultimately derived from those parts of the basin where salts do precipitate at the surface by this mechanism.

The temporal flooding of the basin also accounts for the occurrence of sub/euhedral tabular gypsum crystals within channels (see Figure 7c), which represent a large fraction of the total amount of gypsum in the IVc and IVd horizons at all basin-central sites. Infillings of this type can only form by crystallization at the brine–air interface in brine-filled macropores. Percolation of water through these pores during flooding does not lead to an immediate rise of the groundwater table to attain a new equilibrium position, which is again due to the low hydraulic conductivity of the Unit IV deposits. As a result, the macropores are still filled to a level above the groundwater table when evaporation has increased the concentration of the brine within the pores to a point where saturation is reached. Because high brine levels need to be maintained within the pores, both the

presence of a groundwater table at shallow depth and a low hydraulic conductivity of the groundmass are prerequisites for the development of these gypsum infillings. This is demonstrated by the absence of gypsum infillings at site 36, where groundwater levels are low and where brines cannot stagnate in macropores within Unit IV unless the groundwater table is located above the highly conductive deposits below the base of this interval. At several sites, the deposits contain clusters of smaller euhedral crystals (see Figure 7b), which occur in smaller voids than the sub/euhedral tabular crystals. The current distribution of these clusters, which formed in the same manner as those larger crystals, is related to the dissolution of the gypsum infillings in the course of a later flooding stage. During such an event, small clusters outside the macropores can be preserved, whereas crystals with an equally small size that formed within the macropores are completely dissolved. The larger crystals that occur in those voids are only partly affected during the flooding stages, resulting in the development of non-euhedral forms.

Gypsum crystals in Unit II cannot have formed as groundwater precipitates that developed after the deposition of Unit III, in view of the properties of the latter with regard to water movement. Instead, they must have formed before the deposition of the Unit III sediments began. The strong similarity between the deposits of Units II and IV shows that the nature of the lake was similar during both stages. The formation of Unit II is therefore likely to have also been followed by a period of subaerial exposure with groundwater deposition of gypsum, resulting in the development of a gypsum occurrence that is similar to the one in Unit IV. Part of this gypsum has been preserved unaltered in the lower part of the interval at one site (site 35) and may also still occur elsewhere. The large hemi-bipyramidal crystals at the top of the interval probably formed by recrystallization, following an interaction of the pedogenic gypsum with lake waters and subsequently with the groundwater that is periodically contained in the overlying unit. An interaction with groundwater can also explain the occurrence of the same type of crystals in the lower part of Unit II at site 35, where brines are contained in the upper part of Unit I.

Distribution patterns: kalistrontite

Kalistrontite ($K_2Sr(SO_4)_2$) is a rare evaporite mineral that has previously been identified only for Permian strata (Voronova, 1962; Bader and Böhm, 1966). In the Omongwa basin, it occurs near the southwestern margin (sites 2, 30, 31 and 32) and at site 38. In all profiles, it occurs exclusively along the contact between Units III and IV. At site 38 it forms massive microcrystalline nodules that are up to 3 cm in size. At all other sites it occurs as a thin discontinuous layer that consists both of microcrystalline sections with a xenotopic fabric and of larger sub/euhedral crystals (50–150 μm), with faces of the $\{10\bar{1}1\}$ form and often with narrow $\{10\overline{11}\}$ faces. The kalistrontite layer contains lenticular gypsum crystals in some samples (Figure 7f) and moulds of such crystals in others, documenting the timing of its formation and the solubility of kalistrontite relative to that of gypsum.

The elevated strontium concentrations that are required for the formation of kalistrontite were reached by its enrichment during evaporative concentration of the brines. The pattern of its distribution within the basin is determined by its low solubility, which is certainly markedly lower than that of gypsum. In this way, its occurrence near the southwestern pan margin is related to the existence of a concentration gradient away from the groundwater discharge zone in that part of the basin. Its occurrence at site 38 suggests that a similar gradient exists along the northern pan margin, with kalistrontite precipitation in an area where groundwater salinity is still quite low. Despite the presence of kalistrontite instead of celestite ($SrSO_4$), as well as the presence of minor amounts of other potassium-bearing salt minerals within the deposits, the modern brines do not have an exceptionally high potassium content (Na/K $\approx$ 9 to 11).

The occurrence of kalistrontite near the boundary between Units III and IV implies that the evaporation front was at its lowest possible level at the time of its formation. It therefore formed at a stage when low groundwater levels were maintained, which can occur in response to a decrease in groundwater supply. When the groundwater table is lower, evaporation is less intense, resulting in a reduced steepness of the concentration gradient and a greater distance between the pan margin and the site where saturation is reached. In the Omongwa basin, strontium may normally be removed from solution by celestite formation in marginal parts, whereas kalistrontite is formed during stages with low groundwater levels in more central parts of the

Table II. Main features of the different morphological types of gypsum crystals of the Omongwa pan deposits

Prismatic crystals

- crystal forms (see Figure 6): {120} and {010}, and less well developed $\{\bar{1}11\}$ and $\{\bar{1}03\}$; often flattened parallel to (010)
- zonation: parallel to faces of the euhedral crystals; absent in the surface deposits
- occurrence: eu-to anhedral crystals, in surface horizons and in surficial deposits that locally cover the pan floor
- crystal size: mainly 100 μm to 1 mm

Tabular crystals

- crystal forms: $\{\bar{1}11\}$ and $\{\bar{1}03\}$; {120} and {010} very reduced or absent; equant in cross-sections parallel to $(\bar{1}01)$
- zonation: none
- occurrence
  - clusters of small euhedral crystals in voids or associated with partly dissolved larger (lenticular) crystals, in Unit IV
  - larger sub- to euhedral crystals in channels and some vughs, in Unit IV
- crystal size
  - 10 to 20 μm and 100 to 250 μm as lower and upper size limits for small crystals in clusters
  - 100 to 250 μm and 250 μm to 1 mm as size limits for the larger crystals

Hemi-bipyramidal crystals

- crystal forms (see Figure 6): $\{\bar{1}11\}$ and $\{\bar{1}03\}$; elongated parallel to intersection between $\{\bar{1}11\}$ faces
- zonation: insufficient data
- occurrence: intervals with large gypsum crystals in Unit II
- crystal size: 0·5–3 cm (site 33); 0·3–4 cm (site 34); 0·3–1 cm (site 35)

Lenticular crystals

- crystal forms: curved crystal faces replacing $\{\bar{1}11\}$ and $\{\bar{1}03\}$ faces; flattened parallel to a plane between $(\bar{1}01)$ and $(\bar{1}03)$
- zonation: common in horizons with high gypsum content
  - mainly with lenticular bands or cores: symmetrical overgrowths in cross-sections perpendicular to (010) and the plane of flattening, most strongly asymmetrical overgrowths in cross-sections parallel to (010)
  - less commonly with euhedral bands: tabular forms (cf. tabular crystals, but slightly elongated and with rounded obtuse edges); changes in form between successive bands in some crystals (see text)
- occurrence
  - throughout Unit IV (below the surface horizons) and along voids in the upper part of Unit III, within the sediment matrix
  - Unit II, outside the sections with large hemi-bipyramidal crystals
- crystal size: mainly 250 μm to 2·5 mm

basin, where the residual interstitial brines have a higher potassium content. This hypothesis can only be confirmed by verifying the presence of celestite in more marginal parts than those that were sampled.

Gypsum crystal morphology

Four morphological types of gypsum crystals occur in the studied deposits. The main features of the nature and mode of occurrence of these morphological types are summarized in Table II, and two crystal habits are illustrated in Figure 6. Their distribution is related to the patterns of water movement that have previously been discussed.

The prismatic crystals that occur in the surface horizons and in surficial deposits have a crystal habit derived from a form that is obtained by crystal growth in pure $Ca\text{-}SO_4$ solutions (e.g. Simon and Bienfait, 1965; Edinger, 1973; Van der Voort and Hartmann, 1991) (Figure 7a). Gypsum crystals with this habit have been reported for a number of lakes, as subaqueous precipitates (e.g. Warren, 1982; Bowler and Teller, 1986; Magee, 1991). The prismatic crystals in the Omongwa pan deposits formed partly as precipitates of this type, during the later part of the short flooding stages that affect the basin. Most prismatic crystals, however, developed within the brine-saturated surface layer following flooding events, resulting in the formation of crystals with sediment inclusions. Because the surficial parts of the deposits are periodically pervaded by undersaturated brines, the crystals are predictably only rarely euhedral.

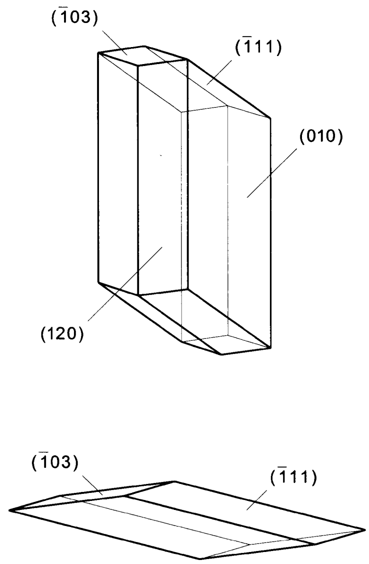

Figure 6. Crystal morphology of prismatic (top) and hemi-bipyramidal (bottom) gypsum crystals

The tabular, hemi-bipyramidal and lenticular crystals all experienced an inhibition of growth in a direction parallel to [001] during their development. For the development of short prismatic forms, this inhibition has been related to the presence of organic compounds (e.g. Lea and Nurse, 1949; Van Rosmalen *et al*., 1976) and less commonly to a high salinity (Cody, 1976) or a high pH (Kirov, 1980). The development of lenticular forms, irrespective of whether (only) a selective growth inhibition is involved, has also been attributed to the presence of organic substances (Cody, 1979; Cody and Cody, 1988) or sodium chloride (Deicha, 1943, p.157; 1946), as well as to high Ca/SO_4 ratios (Kushnir, 1980).

The tabular crystals, which formed within brine-filled voids in Unit IV, have experienced a lesser degree of inhibition of growth in a direction parallel to [001] than the hemibipyramidal and lenticular crystals (Figures 7b and 7c). Occurrences of crystals with this form appear to be rare in natural environments. The only well-documented occurrence (Last and Schweyen, 1985) pertains to subaqueous precipitates, which is compatible with the nature of their occurrence in the studied deposits. The difference in morphology between the tabular crystals and the prismatic crystals of the surface horizon indicates a somewhat greater similarity in composition between the brines in the macropores and those in the matrix of the subsurface horizons than between the former and those in the saturated surface layer.

The development of the large hemi-bipyramidal crystals that occur in parts of Unit II requires stable conditions. The nearly permanently brine-saturated intervals in which these crystals occur, at least at sites 33 and 34, therefore represent expected localities for their occurrence. The occurrences of lenticular and hemi-bipyramidal crystals are in this way restricted to the vadose and phreatic zones respectively of the same profile, which is a type of distribution that has also been described for other basins (Bertrand and Jelisejeff, 1974; Kulke, 1974; Warren, 1982).

A lenticular form characterizes all crystals that formed within the subsurface horizons of Unit IV, outside the void system. This form represents the most common habit of gypsum crystals in soils (e.g. Stoops *et al*., 1978; Eswaran and Zi-Tong, 1991; Jafarzadeh and Burnham, 1992), with the possible exception of acid sulphate soils (e.g. Miedema *et al*., 1974; Bullock *et al*., 1985, p.71; FitzPatrick, 1993, p.72). An understanding of the development of this form is hindered by an uncertainty regarding its crystallographic characteristics. Some authors consider crystals with a lenticular form to be simply hemi-bipyramidal crystals with curved faces and rounded edges (e.g. Siesser and Rogers, 1976; Logan, 1987, p.27). Others recognize

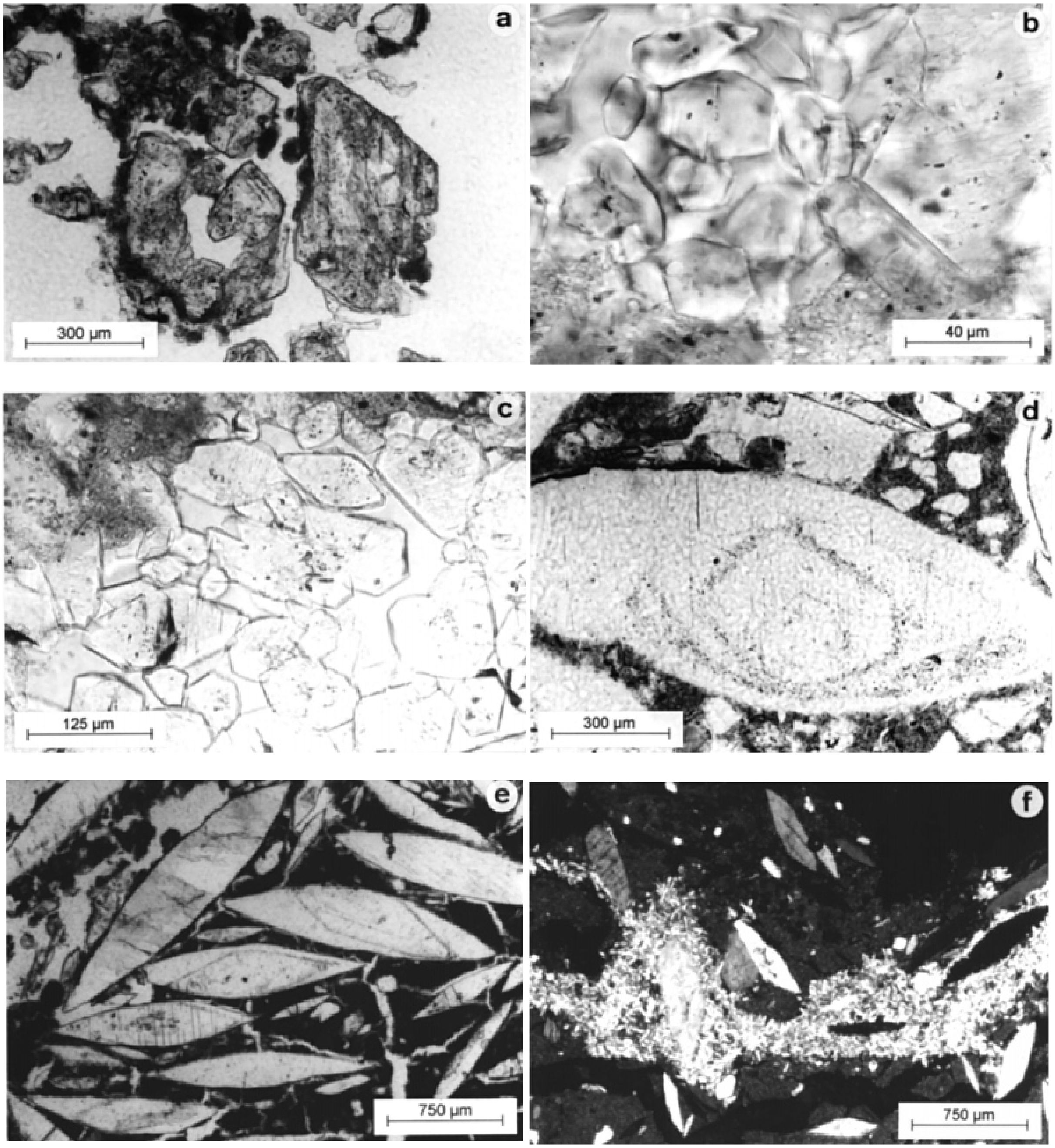

Figure 7. (a) Prismatic gypsum crystals. The large subhedral crystal (right) displays large {120} prism faces, smaller {$\bar{1}$11} faces and a small {$\bar{1}$03} face (top left), in a cross-section parallel to (010) (site 35, IVa horizon; plane-polarized light [PPL]). (b) Small, mainly euhedral, tabular gypsum crystals. All crystals display well-developed {$\bar{1}$11} and {$\bar{1}$03} faces and some have small prism faces of the {120} and {010} forms (site 33, IVc horizon; PPL). (c) Larger subhedral tabular crystals, with the same crystallographic characteristics as the crystals in (b) (site 31, IVc horizon; PPL). (d) Lenticular gypsum crystal with bands of sediment inclusions that record non-lenticular growth stages. The non-lenticular forms display {$\bar{1}$11} faces and, in the inner bands, {010} faces (parallel to the direction of cleavage, which is nearly perpendicular to the plane of the thin section) (site 30, IVc horizon; PPL). (e) Lenticular gypsum crystals with recorded lenticular growth stages. The three crystals in the centre of the image (with nearly horizontal longitudinal axes) illustrate the symmetrical aspect of the overgrowths in cross-sections parallel to {010} (left) and their asymmetry in cross-sections that deviate from that orientation, with a stronger asymmetry with increasing degree of deviation (centre vs right) (site 31, IVe horizon; PPL). (f) Kalistrontite layer, with gypsum crystals as inclusions (site 31, boundary between Units IV and III; cross-polarized light)

lenticular crystals as a distinct morphological type, with larger $\{\bar{1}03\}$ faces than the hemi-bipyramidal crystals (e.g. Cody and Cody, 1988), while appearing to consider the curvature of the crystal faces as an intrinsic property of the $\{\bar{1}11\}$ and $\{\bar{1}03\}$ forms (e.g. Cody, 1979, p.1024). Only Masson (1955) makes a clear distinction between the development of lenticular and hemi-bipyramidal crystals: the former are described as flattened forms with strongly developed $\{\bar{1}03\}$ faces, greatly reduced $\{\bar{1}11\}$ faces, and a lateral extension in a direction parallel to [010].

The restriction of lenticular forms to larger crystals that has been reported for some sites (Masson, 1955; Siesser and Rogers, 1976) suggests that they can develop from euhedral precursors through accretion. The absence of non-lenticular forms in the sediment matrix of Unit IV does not entirely disproof that this also occurred in the studied basin, because the deposits may not contain any crystals with an as yet unmodified habit. The zonation that some crystals display does record the occurrence of non-lenticular growth stages for a small number of crystals (Figure 7d). The frequency of their occurrence is certainly underestimated by the available thin section observations, both because of the absence of non-lenticular cores in cross-sections parallel to (010) and because the conditions for the development of zonation (i.e. the occurrence of variations in growth rates, with incorporative fast growth) are not always met. The scarcity of crystals for which non-lenticular growth stages are recognized, as well as the small size of part of the crystals with a lenticular form, indicates that the development of this crystal habit commonly does not involve the modification of a non-lenticular form.

The few lenticular crystals in which successive euhedral bands have a different form shows that crystal growth is accompanied by a lateral extension that results in the reduction and later disappearance of the {010} faces (Figure 7d). For crystals with lenticular cores or bands, the patterns of zonation also demonstrate that the further growth of lenticular crystals is characterized by a lateral extension, in all directions within the plane of flattening. More importantly, they also record a change in the orientation of the plane of flattening, which remains perpendicular to (010). This results in the development of overgrowths that are symmetrical to strongly asymmetrical, depending on the orientation of the cross-sections (Table II; Figure 7e). These observations show that lenticular and hemi-bipyramidal crystals differ with regard to the orientation of the plane of flattening, which is parallel to $(\bar{1}01)$ in hemi-bipyramidal crystals and parallel to a plane between $(\bar{1}01)$ and $(\bar{1}03)$ in lenticular crystals. Because the curved faces of the lenticular crystals have a $\{\bar{1}11\}$ and a $\{\bar{1}03\}$ component, a change in the relative contribution of these components must account for this shift. In view of the greater size of the $\{\bar{1}03\}$ faces in lenticular than in hemi-bipyramidal crystals, this shift is related to a continued stronger development of the $\{\bar{1}03\}$ form relative to the $\{\bar{1}11\}$ form during further growth of the lenticular crystals. A difference in inhibition of growth parallel to the $\{\bar{1}11\}$ and $\{\bar{1}03\}$ faces is clearly involved in this change, whereby the slower growth parallel to $\{\bar{1}03\}$ that results in their enlargement leads to a change in orientation of the curved crystal faces that replace the pairs of $\{\bar{1}11\}$ and $\{\bar{1}03\}$ faces.

The observations discussed demonstrate that lenticular crystals form under different conditions from those that favour the development of euhedral flattened forms. Possible differences in composition between brines of the vadose and phreatic zones, where the related lenticular and hemi-bipyramidal forms tend to develop, include differences in salinity and ion ratios, as well as differences in the oxidation state of certain compounds. The latter, which occur in response to differences in redox potential between aerated and permanently waterlogged zones, represents a factor whose role has never been assessed by crystal growth experiments.

CONCLUSIONS

Distribution patterns of evaporite minerals that form as groundwater precipitates can be explained by referring to mechanisms of water and solute movement in soils that are subjected to evaporation. A first major factor is recognized to be groundwater depth. An equally important factor is the lithological composition (and hence hydraulic conductivity) of the deposits and its variation with depth. Other factors that affect the evaporite mineral distribution patterns are the redistribution of salts following the flooding of dry lake basins after heavy rains and also the patterns of groundwater flow, which partly determine the lateral variations in

salinity. The principles discussed can be applied to any other site, but their expression will be determined by local conditions, which will commonly not be as favourable for their understanding as in the Omongwa basin.

Different types of gypsum occurrences in the studied deposits are each characterized by a specific crystal habit. Subaqueous precipitates and crystals that developed within a brine-saturated surface layer have a prismatic form that is produced in conditions without a differential growth inhibition of the crystal forms. Crystals that formed within brine-filled macropores have a tabular form, characterized by a rather limited degree of differential inhibition of growth, whereas intrasediment growth in the vadose zone produces lenticular crystals, whose development requires a stronger differential growth inhibition. The hemi-bipyramidal crystals, with an intermediate reduction of growth rates for the $\{\bar{1}03\}$ form, are the product of recrystallization of gypsum within a nearly permanently waterlogged interval in lower parts of the deposits. Although this study does not allow identification of the factor that is responsible for the differential inhibition of growth, it does indicate that, rather than the presence or abundance of a simple compound, the creation of potentially active groups in certain conditions and/or the prevention of their interaction with gypsum crystals may be involved. The recognition of major differences in gypsum crystal habit between subenvironments of the same profile suggests that future research should be directed towards identifying compounds whose nature and behaviour are different in those various sections.

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